HIGH-G TESTING OF ELECTRONIC COMPONENTS

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THESIS

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ABSTRACT

High-g acceleration produced by large bore guns is compared with impact acceleration. Methods for subjecting electronic components and circuit packages to high-g launch environments up to 550, 000-g are outlined and analyzed. An analysis of the effect of the high-g environment on components is performed on a component by component basis. Methods for selecting, "hardening" and testing components for high-g circuitry are given as are circuit construction and assembly details. An extensive appendix listing type, manufacturer and part number is included for components that have survived high-g environmental testing. Recommendations are made for an improved test program that will yield a new generation of reliable high-g hardened components for circuit design.

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I. INTRODUCTION

The rapidly advancing state of the art in circuit miniaturization and in microminiature integrated circuit makes it more and more inviting to construct electronic components for various uses in gun fired projectiles. Present circuits are certainly adequate for the needs of these advanced weapons; however, the environmental capability of the components used to construct these circuits is just beginning detailed technological investigation and development.

The environmental requirement most urgently in need of investigation is that of the extremely high accelerations these circuits and components must withstand. The least severe of these accelerations is about 8000-g (8000 times the acceleration due to gravity). Some "state-of-the-art" accelerations are expected to reach as high as 4, 000, 000-g. It is obvious that "standard" component construction techniques and circuit assembly methods may not be adequate for these environments.

An additional consideration is the interdependence of power handling ability and tolerance to thermal shock. The thermal shock consideration becomes associated with the high-g launch environment due to component and circuit construction techniques requiring complete encapsulation. This requirement significantly alters the power handling capability of the individual components. For a surface launched, high flying projectile the barrel temperature due to propellant gases and friction may exceed the normal MIL-SPEC electronic component temperature limit (-65° to $+158^{\circ}$F.) by an order of magnitude or more while only a few seconds may elapse until the projectile has reached

an ambient temperature environment in the upper atmosphere of about -60°F. In addition lower atmospheric aerodynamic heating can cause projectile temperature on the order of 300°F.

The high-g environment, with nominal peak accelerations on the order of 50,000-g is common place in today's large bore (5-inch and larger) guns while significantly higher accelerations result from small bore weapons. These accelerations differ dramatically from an impulse such as may be experienced from a drop, or impact, in that they typically last for several milliseconds as compared to a maximum of one or two microseconds for an impact. A comparison of several launch acceleration profiles and an impact profile may be seen in figures 1, 2, 3 and 4. While the peak accelerations are obviously a function of the mechanisms producing them, the time spans are typical of those experienced during launch and impact.

The acceleration pulse profiles shown in figures 1 and 2 were calculated by the Ballistic Research Laboratories (references 1 and 2). Figure 1 is based on theoretical maximum breech pressure while figure 2 is a result of measured breech pressure. In both cases the profiles represent the maximum available acceleration considering stiction (i.e., projectile "sticks" in barrel until maximum pressure is reached then moves initially with no friction) which is the "worst case" condition. The actual acceleration normally experienced by the projectile is about half that shown.

Figure 3 is indicative of the time duration of an impact as determined by Brody (reference 3) in his experimentation of shock waves in ceramic elements. The short time duration of impacts has been further substantiated by Graham (reference 4) in his studies of

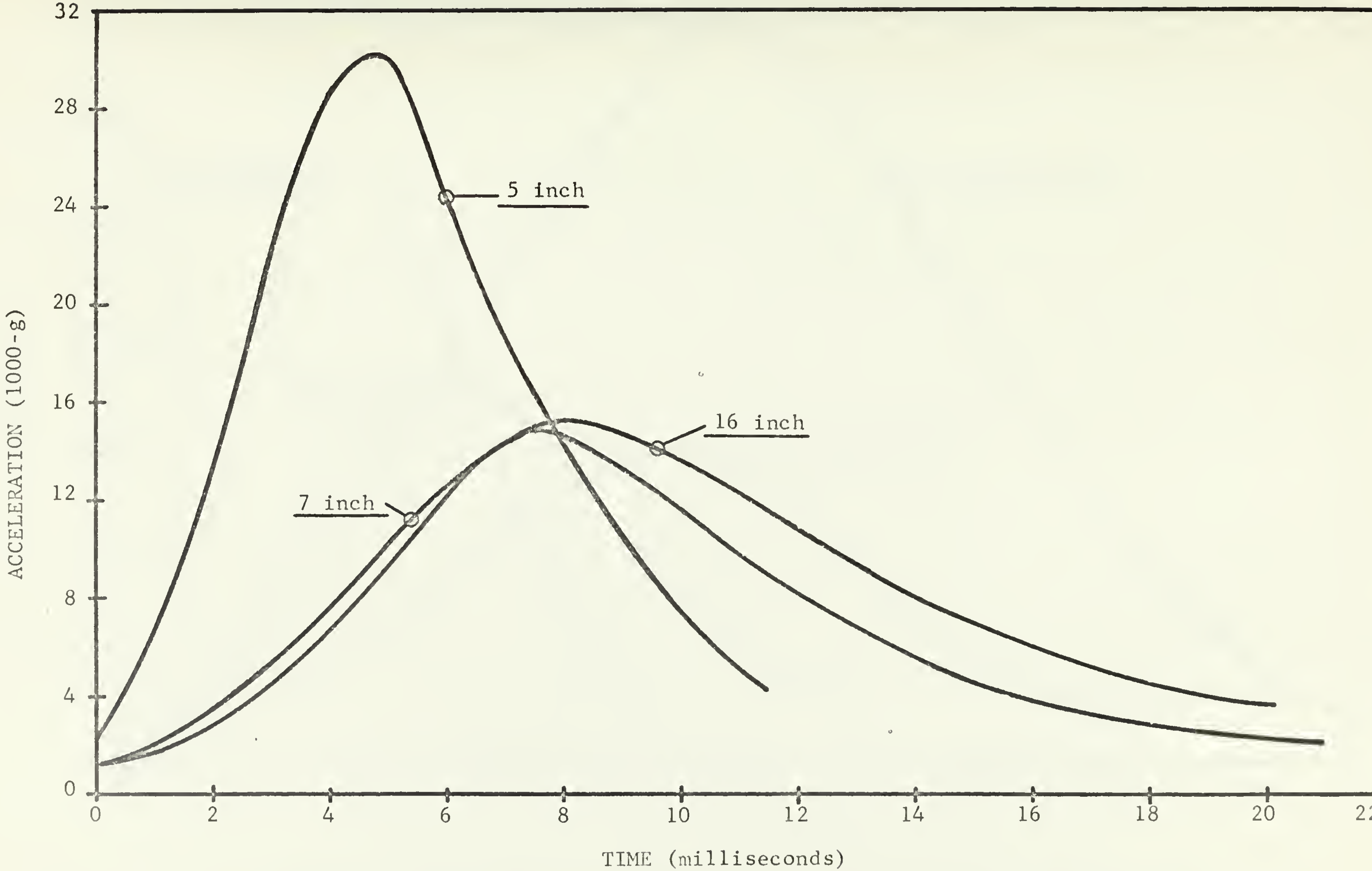

FIGURE 1 - THEORETICAL PROJECTILE LAUNCH ACCELERATION VS TIME PROFILES

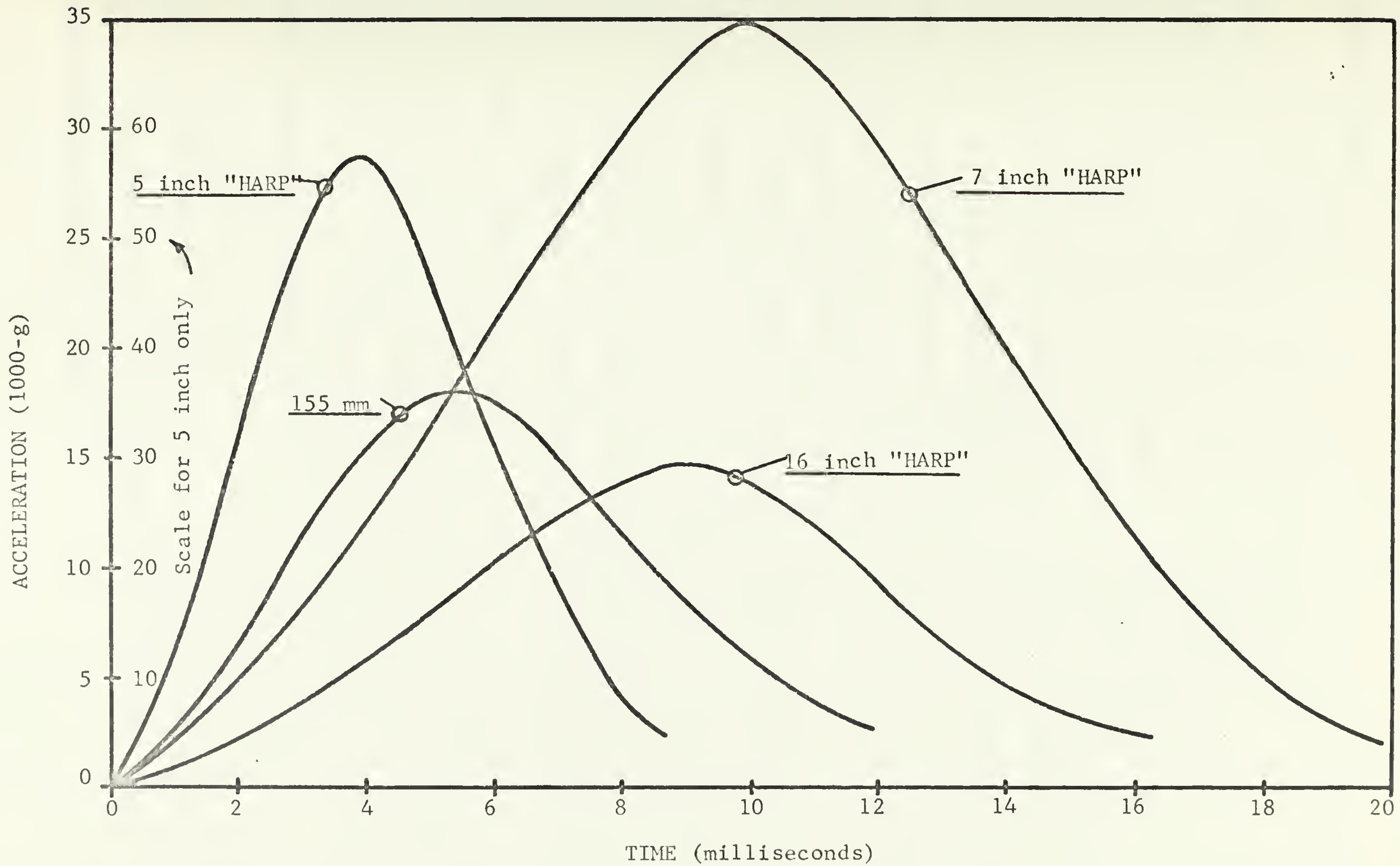

FIGURE 2 - CALCULATED PROJECTILE LAUNCH ACCELERATION VS. TIME PROFILES

piezoelectricity under transient high stress conditions; the profile is shown in figure 4.

Since the primary source of these high-g induced forces is from gun launch of projectiles, one must also consider the acceleration due to spin if present. This effect may or may not be significant depending on the mechanisms of the environment. For most spin stabalized projectiles the maximum acceleration available at the circumference of the projectile (worst case) is of the same order of magnitude as the launch acceleration. The resultant force on any components subjected to this environment is therefore not unidirectional but is a vector beginning parallel to the barrel axis changing to perpendicular in the length of time the projectile is in the barrel.

The alternative condition is one of a smooth-bore firing where the round is stabilized in flight by means other than its own spin. The resultant roll, if any, is very small compared to that of a spin stabilized projectile. In this case the acceleration of interest exists only while the projectile is in the barrel; it no longer changes direction as described previously.

The high-g hardening design of an electronic package must consider the fact that the acceleration changes direction very rapidly during the first few milliseconds of movement for spinning projectiles and is essentially unidirectional for smooth-bore launches.

At the present time there are several techniques being utilized for testing components, circuits and assembly methods under severe acceleration conditions. These techniques may be broken into the following broad general categories:

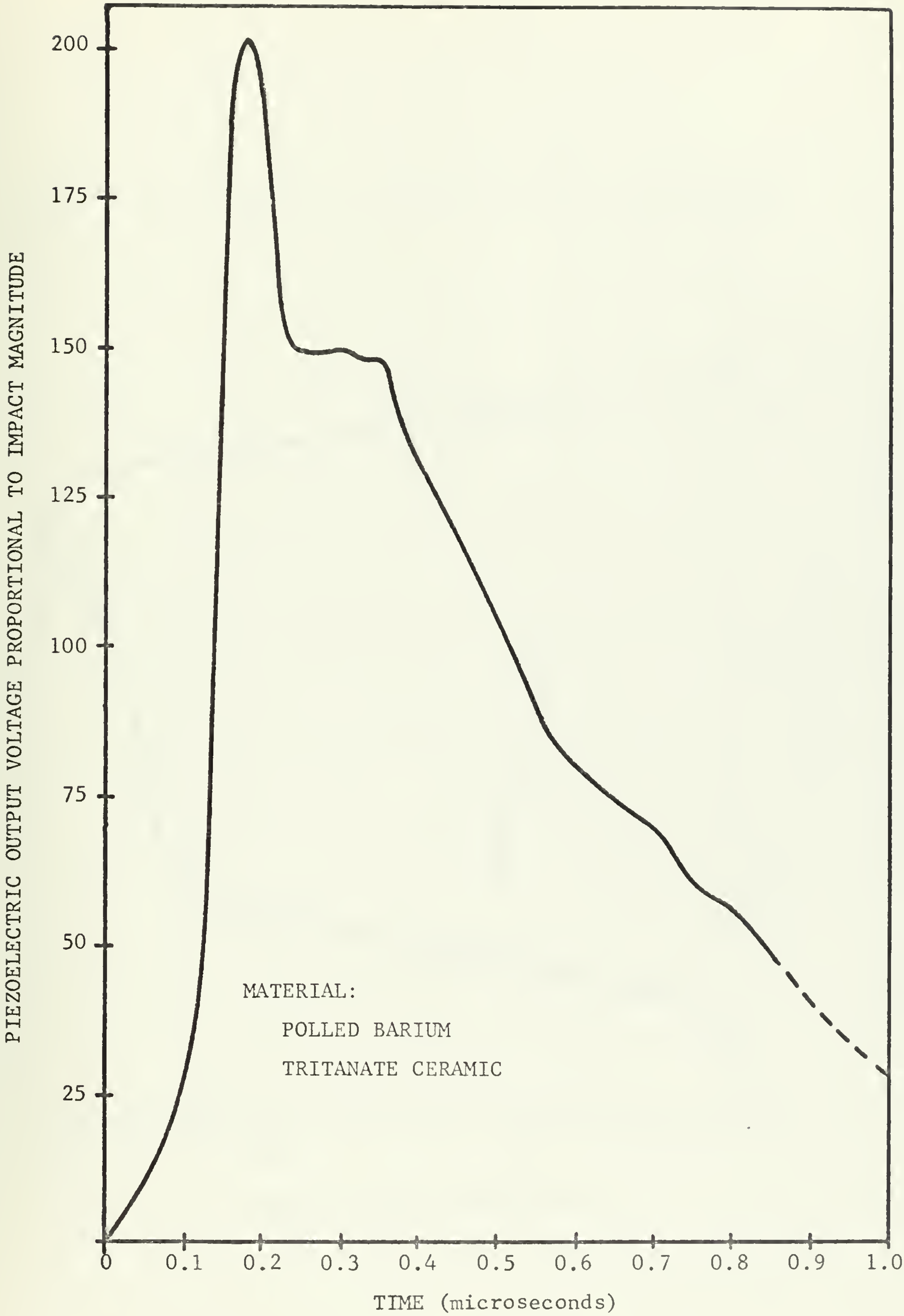

FIGURE 3- PIEZOELECTRIC RESPONSE VS. TIME FOR IMPACT

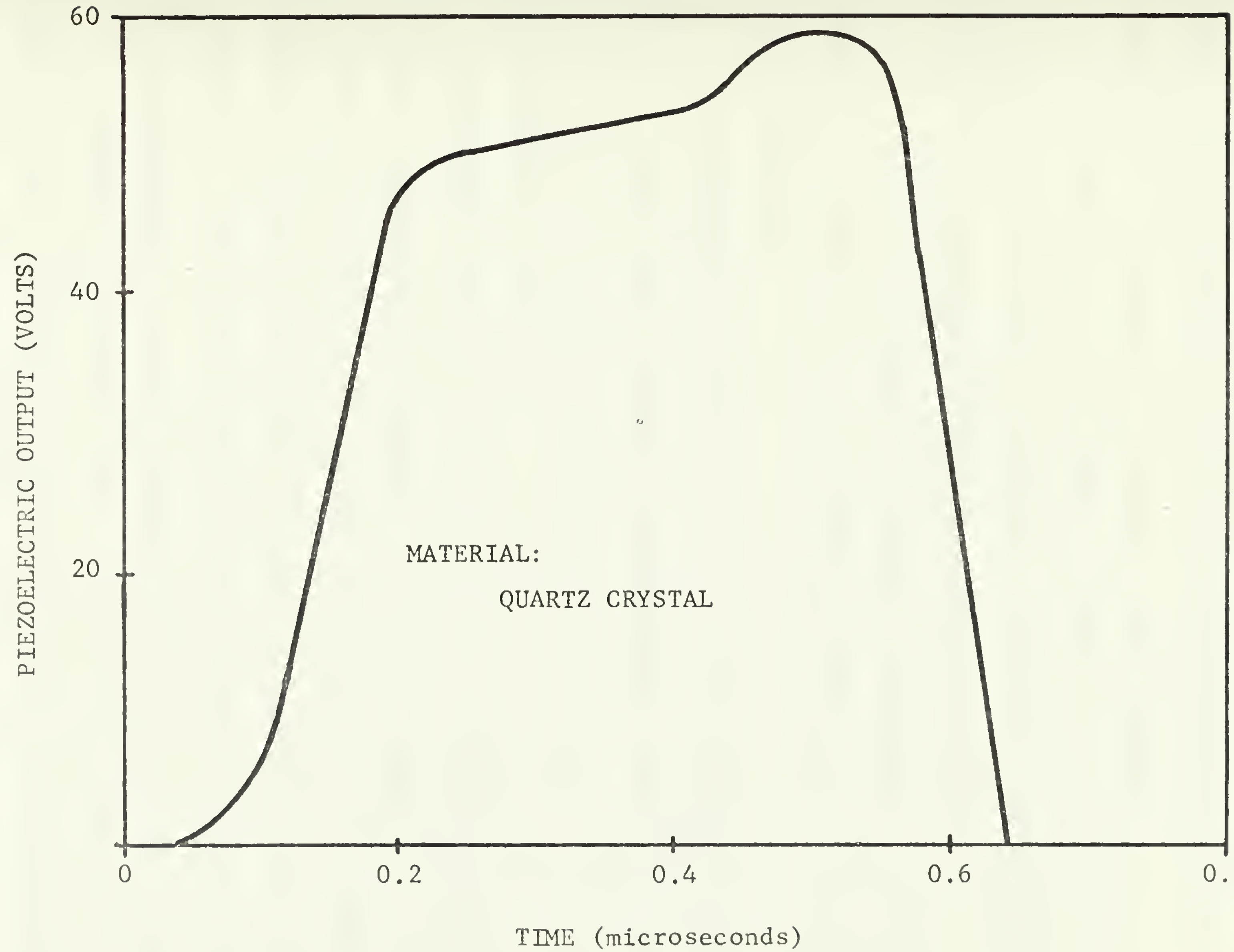

FIGURE 4 - PIEZOELECTRIC RESPONSE VS. TIME FOR IMPACT

1. A high acceleration launch followed by a soft recovery which may be accomplished in several different ways.

2. A high acceleration launch with no attempt being made at recovery; in this case the required scientific data is telemetered back to a processing point. The accuracy and precision of the telemetry itself is questionable due to the high-g launch.

3. A low acceleration launch followed closely by a high deceleration impact with the objective being to simulate the environment of a high launch acceleration with the deceleration impulse.

4. Centrifuge testing which cannot simulate the short duration application of the actual acceleration pulse but may be closely controlled otherwise.

One phenomenon common to all but the most recent "state-of-the-art" tests is that the components in question are pre-launch tested, launched then post-launch tested; the dynamic effect of in-barrel acceleration is not monitored.

One question must be considered at this point since the first two techniques involve both acceleration and deceleration prior to data collection and the third technique has the stigma of questionable telemetry validity: is the effect of high acceleration at least partially reversible? If this is the case the effect being measured by present testing techniques is only partially indicative of the actual acceleration effect on the component. It is, of course, indicative of the net <u>trend</u> of change in component value produced by acceleration followed by deceleration for the first two cases. In the case of telemetered data the result could possibly be statistically validated after a long, complex and costly test program. For instance it may only be known

that a resistor may increase or decrease in value or the h-parameters of a semiconductor may increase or decrease. The reliability of any quantitative data is, at best, questionable.

If the electronic circuitry in the projectile is to produce a given result following a launch but preceding impact, additional, more accurate information on component/circuit change is needed. In general a test program should be initiated that will: (1) promptly and inexpensively eliminate any components susceptible to catastrophic failure and (2) determine the actual dynamic change in component values during and following actual launch but prior to impact. This test program should include assembly methods as well as component and circuit performance validation. The information thus obtained would allow the design engineer to produce complete circuits that may be pre-flight tested to one set of pre high-g environment specifications and still perform predictably to a different specification following launch.

The present testing techniques are marginally adequate in that they: (1) identify most components susceptible to catastrophic failure, (2) they determine only the trend of change of parameter values. This information may then be utilized by the design engineer to design a circuit on which he must perform a sensitivity analysis (references 5 and 6) and eliminate or change any components that may obviously cause problems. Since the design engineer does not know the actual parameter values following launch and prior to impact, he must then construct the circuit and actually flight-test it in order to determine its ultimate performance. Pre-launch circuit test and alignment becomes, at best, questionable when attempting to provide predictable post-launch performance.

The following section of this report provides a more detailed description and analysis of the four major testing techniques presently in use. Section III is a summary of the effects of exposure to the high-g environment on various components with a detailed list of high-g proven components tabulated in Appendix A.

Recommended techniques for constructing high-g capable electronic packages appears in Section IV. The techniques given are based on methods shown to be successful by past and present test programs. Conclusions and recommendations for further tests and follow on programs is given in Section V.

II. TESTING TECHNIQUES

A. GENERAL

The various methods of mounting the components or electronic circuit packages to be tested is common to most all testing techniques. The most desirable method of mounting these components or subassemblies for testing is the actual configuration in which they will be used. This, however, is not a practical method for testing individual components as encapsulation requires time consuming dissolving of the encapsulant with the possibility of physical damage to the component not caused directly by exposure to the high-g environment. This procedure reduces the reliability of such tests and leads to expensive procedures if used.

One convenient method of supporting the components other than plastic encapsulation has been developed by the Ballistic Research Laboratories of the Army Material Command (Ref. 2). This method is useful particularly for irregular shaped assemblies. It consists of packing the item in a strong container filled with soapstone powder which is tamped (compressed) tightly around the item. It was found that following accelerations of up to 25,000-g's the powder falls off readily from the sample. At 50,000-g's it compacts very firmly but can be chipped away easily. This is obviously a much cleaner, quicker and more efficient technique than encapsulating a component for high-g testing and then dissolving the encapsulant to retrieve the component for inspection or electrical testing. Figure 5 illustrates the method used by the Ballistic Research Laboratories in their soapstone high-g test container.

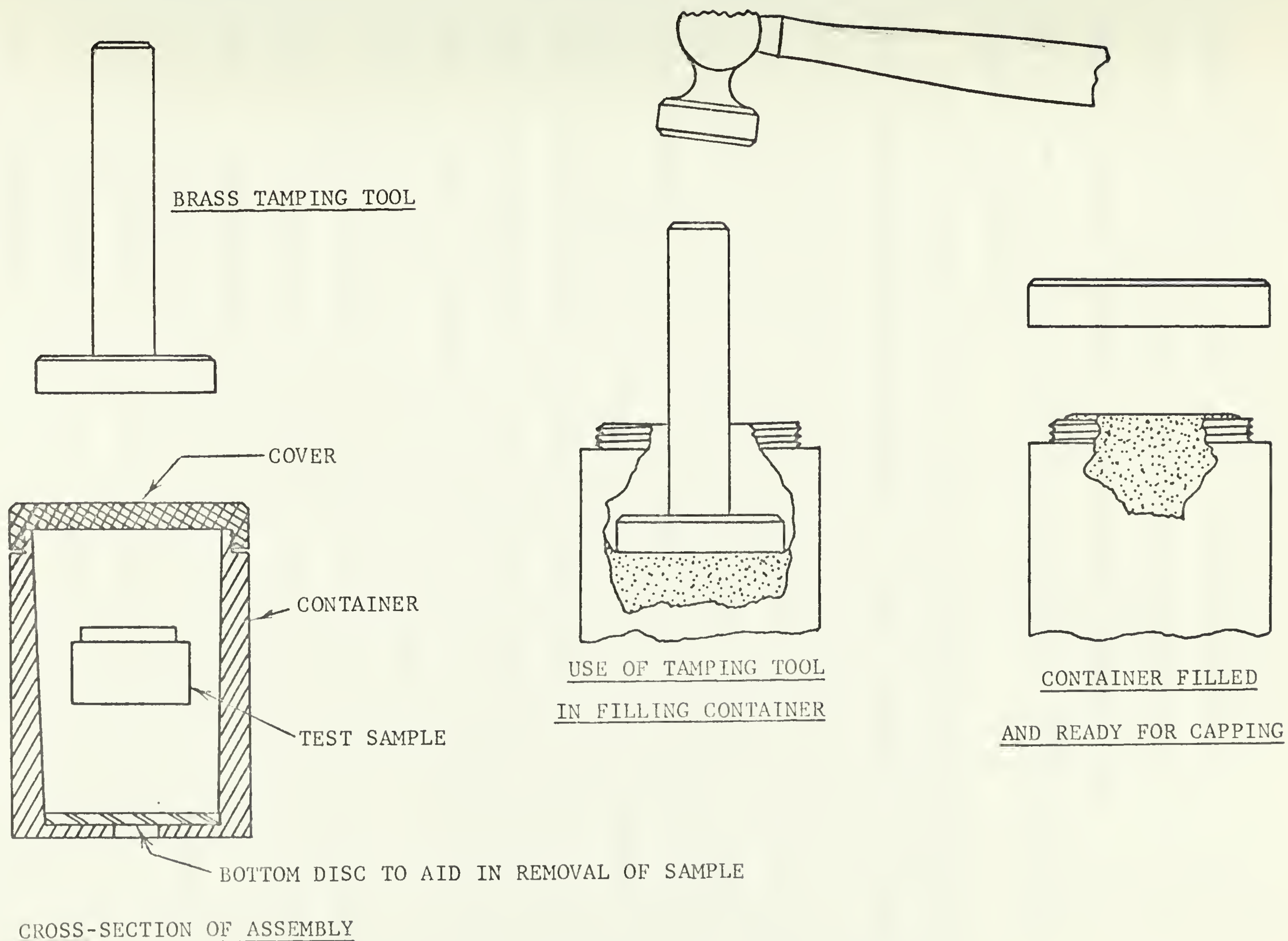

FIGURE 5 - BRL SOAPSTONE HIGH-G TEST CONTAINER

B. HIGH-G LAUNCH WITH SOFT RECOVERY

This technique is perhaps the most predominant throughout the research agencies at this time. It consists primarily of a high-g launch with the magnitude of acceleration being determined by the type and amount of powder and the weight of the projectile. This method can use either a rifled or a smooth-bore barrel depending upon the result desired.

There are many different recovery techniques employed all using basically identical launch techniques. Texas Instrument Corporation, in a joint project with and under contract to the Naval Weapons Laboratory (reference 7), has recently completed a series of tests utilizing this technique. In these tests they used three methods of recovery. The first method was to fire the projectile at short range into a container of sawdust. The second method was to fire the projectile into the water and energize a floatation system thereby enabling recovery. The third method was to fire the projectile and deploy a parachute to slow its flight and descent into the water; the same type of floatation mechanism was then actuated and recovery effected.

One major difficulty encountered by the Naval Weapons Laboratory was the utilization of a firing range with the recovery area in shallow water. Following splashdown the projectile would penetrate through to the mud bottom and become entrapped whereupon the floatation system was unable to bring the projectile back to the surface. This led to a great deal of difficulty in recovery of the projectile. It has been recommended by the Naval Weapons Laboratory that future tests of this type include a sonar pinger as part of the payload to help in the location and recovery of the projectile. A firing range with a

deep-water recovery zone would also alleviate the problem.

Other activities have successfully utilized a soft recovery system which is essentially the firing of a projectile into a tapered gas-sealed barrel thereby slowing the projectile at a predetermined rate depending upon the taper of the recovery barrel, the type and amount of gas contained within the barrel, and the size and number of vents allowing the compressed gas in the barrel to escape.

Harry Diamond Laboratories (references 8 and 9)have also successfully recovered projectiles in a long, large enclosure filled with sawdust or small particles of styrofoam.

C. HIGH-G LAUNCH WITH TELEMETRY DATA

This technique was used during project FLARE by the Space Research Corporation (reference 10) under contract to the Naval Weapons Laboratory. It consists of a specially constructed projectile which optically senses energy from a flare. The spinning projectile generated pulses as the side-looking optical sensors scanned past the radiation source on each rotation. This pulse signal was then telemetered to a control point thereby providing an audio indication of complete system operation. No attempt was made to recover the projectiles as a part of the high-g telemetry test; however, recovered projectiles did confirm structural integrity of the payloads.

Space Research Corporation's objective was to demonstrate feasibility of equipping a projectile with a sensor system capable of withstanding the high-g environment of a gun launch. The system electronics consisted of a photovoltaic cell whose output was amplified by onboard electronics and then telemetered back to a receiving station

at the launch site. Onboard telemetry utilized an antenna mounted in the base of the projectile. The weapon used was a 155 mm gun capable of producing a 10,000 to 14,000-g and a nominal spin rate of approximately 200 rps. The test program was deemed successful in that 5 out of 6 launches returned telemetry data.

At the High-g Session of the International Telemetering Conference, 1970 (reference 11), Sandia Corporation, supported by the United States Atomic Energy Commission, reported on their ongoing effort to develop a projectile telemetry system and the required ground support to monitor the performance of components mounted in 155 mm projectiles during launch as well as in flight. The projectile is to experience a 16,500-g acceleration of 15 milliseconds duration coupled with a peak angular acceleration of 328,000 rad./sec^2. A P-band FM telemetry system has been developed to provide a data link while the projectile is in the barrel as well as in flight. The technique was reported to have been successfully tested at accelerations of 12,500-g for 20 milliseconds. The system also used a parachute to obtain a soft recovery of the projectile thereby enabling post-flight testing of components and telemetry systems if desired.

This in-barrel transmission link required a special technique; since the cutoff frequency for the TE_{11} mode in the 155 mm barrel was 1100 MHz it could not be used as a waveguide for the UHF transmissions (230.4 MHz). The attenuation in the barrel was approximately 60 db/ft thus no useable signal strength could be obtained at the muzzle of the 20 ft barrel while the projectile was being launched.

It was discovered during in-barrel tests of the normally self-contained projectile transmitter that external power supply leads were

coupling the RF signal out of the gun barrel and reradiating sufficient energy to be received on the telemetry receiver.

Since, under normal operating conditions, the projectile is a closed system with no external leads, an external wire had to be provided to couple the RF energy out of the barrel. This was accomplished by loosely attaching a loop of wire to the nose of the projectile in close proximity to the telemetry antenna. This wire was terminated at the input to a receiver to provide a hardware link for the RF energy as well as reradiation. No attempt was made to "catch" the wire as the projectile traversed the barrel, rather the wire was "chewed up" by the projectile.

At the time this information was presented 19 tests had been conducted with telemetry data being obtained on 6 of the tests and in-barrel data obtained on 4 of these 6 tests. At least 5 of the failures were attributed to failure of NiCad batteries due to the high angular acceleration. Acceleration data were sensed by piezoelectric and piezorestrictive transducers.

These data were telemetered to the ground station and correlated with data calculated from breech pressures to within 10%. Figure 6 is a plot of the actual inbarrel telemetered acceleration profile which may be compared to the Ballistic Research Laboratories' calculated profile for the 155 mm gun as shown in figure 2.

D. LOW-G LAUNCH WITH HARD RECOVERY

At the present time the Ballistic Research Laboratories (reference 1) are the primary user of this particular technique. It was developed by them in 1966 to proof test telemetry electronics to be utilized in the HARP Projectile System. This test technique consisted essentially

FIGURE 6 - ACTUAL 155mm IN-BARREL TELEMETERED ACCELERATION VS. TIME PROFILE

of a low muzzle velocity firing (500 to 1400 ft/sec, approximately 1000-g or less) from a smooth-bore 5-inch gun for the purpose of exploring the effects produced when test projectiles strike lead targets. The deceleration magnitude and duration is controllable over a limited range by impact velocity, the shape of the projectile nose cones (tips) and the target size. High speed photography and copper ball accelerometers were used to monitor the accelerations and decelerations during these tests.

It was determined that the deceleration was very nearly an impulse; that is, the duration was extremely short compared to that experienced in actual launch situations. Figure 7 is representative of the Ballistic Research Laboratories impact deceleration impulse. The difference in time and shape is obvious when compared with figures 1 and 2.

In order for the Ballistic Research Laboratories to validate this test technique it was necessary to determine the frequency spectrum of both the deceleration profile obtained with their controlled impact and the acceleration profile obtained by launch. Upon comparison of these spectra, shown in figure 8, it was determined that the impluse produced by impacting a lead mass was significantly different than the actual launch acceleration.

For an accurate analysis a linear relationship between the two pulses being compared must be shown. While the Ballistic Research Laboratories have not explicitly shown this relationship, they have authenticated the comparison by successful test results.

To assure proper exposure of the items being tested to the desired accelerations, it was necessary to "over test" the items.

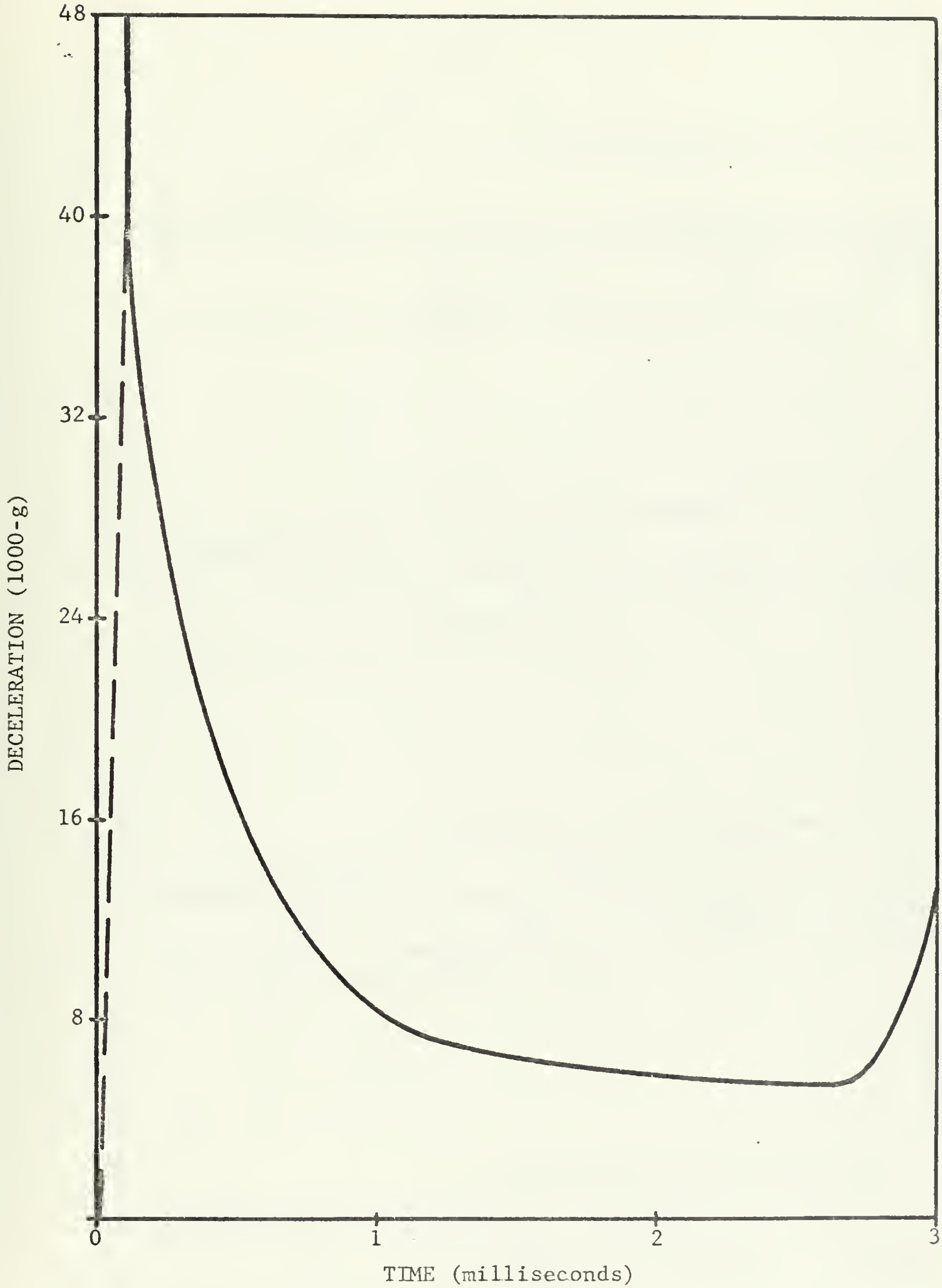

FIGURE 7 - BRL LEAD IMPACT DECELERATION VS. TIME PROFILE

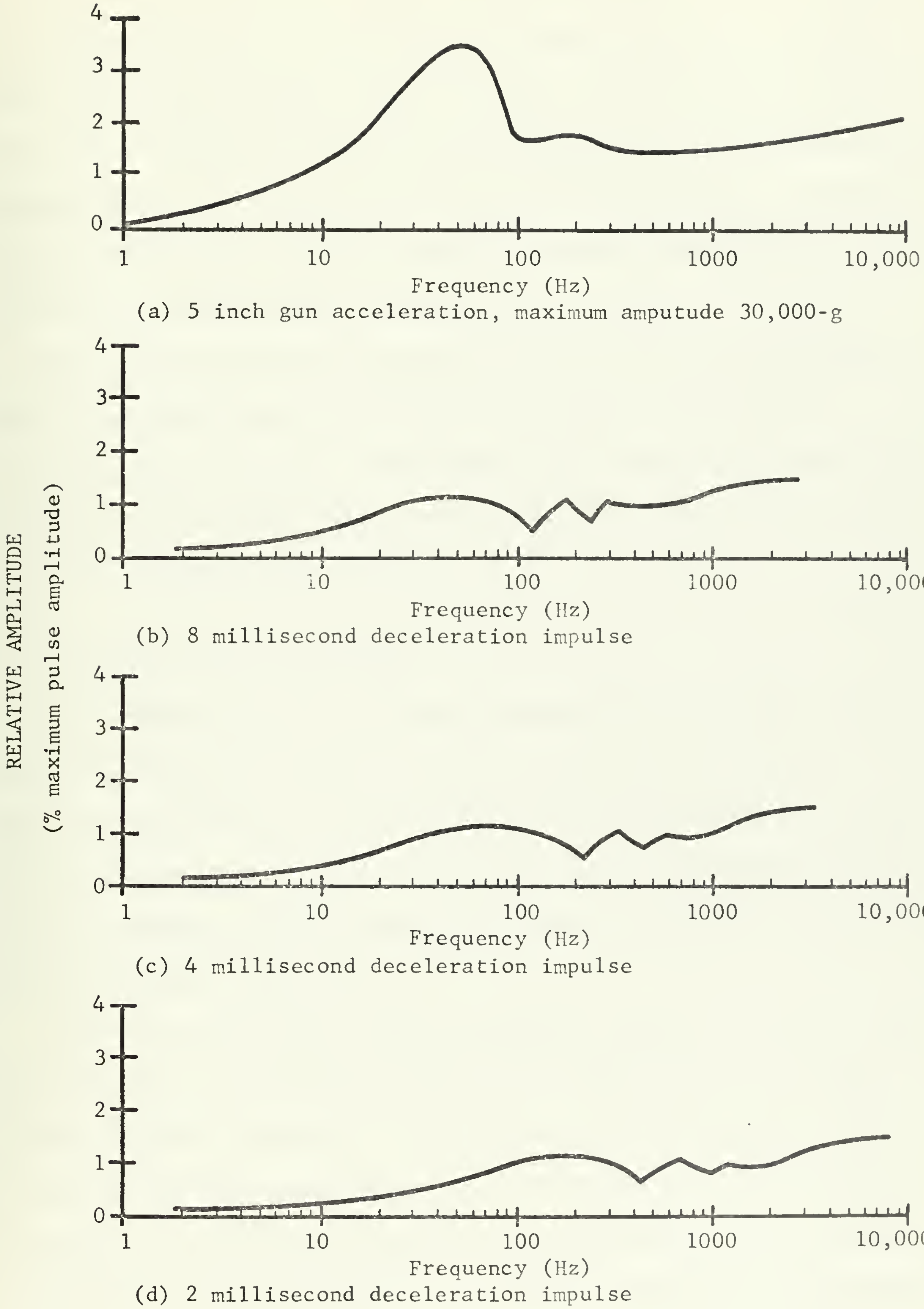

FIGURE 8 - BRL FOURIER SPECTRA

In order to reduce the over test as much as possible, it was decided by the Ballistic Research Laboratories to include frequencies between 100 Hz and 10, 000 Hz in their tests criteria. It was determined that they could simulate a 40, 000 to 50, 000-g launch of 10 to 15 milliseconds duration with an impact impulse of approximately 62, 000-g of duration about 3 milliseconds. The impulse thus produced should contain equal or greater magnitude of all frequencies above 85 Hz.

Harry Diamond Labs (reference 12) has a similar "lead-impact" test facility which uses a 4 inch air powered gun for the launch mechanism in place of the 5 inch smooth bore conventional propellant gun used by the Ballistic Research Laboratories. Both facilities have produced significant useful data.

E. CENTRIFUGE TECHNIQUES

The mechanics of the centrifuge techniques used for electronic component testing are similar to those used with any centrifuge: mounting the item to be subjected to the acceleration near the circumference of a rotating machine. This test method is generally limited to a few thousand g's with a slow rate of onset; however, it is presently in use at several installations.

Harry Diamond Labs (references 8 and 9) employs a unique centrifuge technique in combination with the low-g launch/hard recovery method explained previously. In this type of test the component is mounted in a test slug and fired from a compressed air gun at a low accleration. The test slug impacts on a spinning disk covered with 4-inch thick aluminum honeycomb. The slug collapses the honeycomb thereby providing a predictable deceleration of 8, 000 to 10, 000-g.

Simultaneously with impact, the slug is spun up to provide the radial acceleration. The present equipment is limited to a spin rate of about 7,200 rpm (approximately 1/2 the rate of a 155 mm production projectile). The low magnitudes of acceleration (deceleration) and spin rate preclude the use of this system on other than a limited basis. It does, however, simulate the rapidly changing acceleration vector (explained in the introduction) in an "external", observable manner.

Since the acceleration vector of a spinning projectile is approximately constant in magnitude throughout the flight of the projectile, the centrifuge technique may have increased application in future test programs. Not only will this technique provide information on catastrophic failures in a very economical fashion but will also show the effect of continued exposure to the high-g environment. This method of testing could also be adapted to show the dynamic operation of circuits and to measure the parameters of circuit components during actual acceleration. This course of action has apparently not been intensely pursued although Appendix A of this report does contain a small percentage of information on components which was derived from centriguge testing by various activities.

III. EFFECT ON COMPONENTS

A. GENERAL

This section deals with the effect on electronic components when subjected to a high-g environment. The information herein is a result of correlation of test results from many different agencies performing high-g environmental testing and is presented as an introduction and basis for recommended construction techniques to be addressed in subsequent sections.

There are three basic deficiencies which were predominant in all high-g testing of electronic components. These are (1) voids within the specific components either intentional or unintentional, (2) inadequate methods of terminal connections and (3) hair-line cracks in thin film etched circuitry.

Appendix A is a compilation in abbreviated form of a number of electronic components which have been successfully tested individually and/or as a circuit element.

B. ANTENNAS

The basic design criteria for antennas is one of transmission or reception pattern rather than one of the actual environment. The Ballistic Research Laboratories have done extensive investigation of antennas and for the majority of their telemetry work they have selected either a Scimitar or a Halo antenna. Their investigation has extended to other types of antennas; however, these were not developed to the ruggedized flight model stage.

Other configurations considered were: (1) flush logrithimic spiral, (2) flush slot, (3) flush helix in cavity, (4) flush loop in cavity, (5) stub for body feed, (6) unbalanced loop for body feed and (7) wrap around quadraloop for body feed. These antennas are illustrated and discussed in detail in references 2 and 13. Since each high-g project requires a specific unique antenna configuration no further attempt will be made in this paper to elaborate on these antennas.

The most predominant antenna construction material was found to be polyphenylinoxide (PPO) which is a plastic material having excellent mechanical strength and electric properties for this application. This material was used by Space Research Corporation (reference 10) in their high-g antennas which were subjected directly (without shielding) to aerodynamic heating.

It was found that PPO grade 691-111, manufactured by General Electric in powder form suitable for compression molding, has a dissipation factor typically below 0.001 for frequencies up to 3 GHz within a temperature range from minus 100^{o}F. to plus 350^{o}F. Space Research Corporation did, however, encounter minor problems in machining it if the local temperatures of the machining tool were allowed to exceed the upper temperature given.

For lower frequency applications another grade of PPO (NOREL) is available which overcomes the problem of machine tooling heat distortion. However, the upper frequency limit of the PPO-NOREL was found to be only about 250 MHz.

C. BATTERIES

Batteries are available in a wide variety of sizes and capacities that are usable for the high-g environment. Standard nickel-cadmium

button cells have been used successfully by the Ballistic Research Laboratories in their high-g telemetry programs. However, they have found that the commercially assembled stacks usually have to be vacuum encapsulated to fill the voids between the cells. For reliable use of the large voltage units (cell stacks) at 50, 000-g it was found necessary to purchase them as separate cells and spot weld them together with 0. 006 inch thick stainless steel strips 1/4 inch wide. The commercially assembled cell stacks usually have a connecting strip that is too weak to withstand 50, 000-g. Ballistic Research Laboratories (reference 14) have successfully used nickel-cadmium cells to over 100, 000-g; however, they have experienced physical deformation even after potting sufficient to preclude recharging or reuse.

For use up to 20, 000-g a silver oxide button cell has been used very successfully and has been found to be very convenient, low in cost and reliable. In addition the silver oxide button cells may be used as purchased for spinning projectiles. For higher-g environments the silver oxide button cells also have to be vacuum encapsulated as it was found that as purchased they often had voids in the potting.

A shock and spin actuated liquid electrolyte battery was also used by the Ballistic Research Laboratories in their telemetry system reported on in reference 13.

Experimentation with a battery utilizing liquid ammonia was conducted by Sandia (reference 11) due to its ability to operate in temperatures as low as -65°F. It was found that this battery was capable of operation only if centerline mounted as off axis mounting caused shorting of plates. Space Research Corporation (reference 10) also experienced a great deal of difficulty with ammonia cells.

It was found by Space Research Corporation (reference 10) that the NiCad and silver oxide batteries both had only a 10 minute life after exposure to the high-g shock. It was found by all reporting atencies that battery operation of hardened battery pack units was sufficiently similar to the manufacturer's specifications to be fully usefully.

D. CAPACITORS

It was found by Space Research Corporation (reference 10) that the most suitable capacitor for gun launched applications is the dipped silver mica capacitor. These are available in various sizes depending primarily upon the capacity required. Small ceramic feed thru capacitors such as the Erie Cermicons are also used with a great deal of success by Space Research Corporation.

For polarized capacitor applications the solid tantalum type is used with a great degree of success by most agencies. Any form of wet electrolyte polarized capacitors were found to be totally unacceptable. This includes some "wet slug" tantalum capacitors which failed completely when tested by Aviation Electric, Limited (reference 15).

Milar dielectric capacitors were proven reliable by Aviation Electric, Limited tests. In the very few isolated instances of increased capacitance the maximum was 2.2% of the rated value.

Small trimmer capacitors not containing glass dielectrics were found to be reliable while in most cases the glass dielectric trimmers failed as did most ceramic tubular capacitors.

In the majority of test results reported by Aviation Electric, Limited, the high-g environment decreased the value by amounts varying from 0.1 to 11%.

E. COAXIAL CABLE

Coaxial cable of all types is, in general, considered to be quite reliable. Two major areas of concern must be kept in mind however: (1) the ability of the encapsulating material to adhere to the braid or shielding and (2) the type and ruggedness of connectors used.

F. CONNECTORS

For coaxial cable use, the standard BNC and Microdot connectors are most evident. For wire terminal connectors in circuit construction the Ballistic Research Laboratories (reference 10) recommends the use of a gold plated grommet thru which the small circuit connecting wires are inserted and solidly soldered in place.

The major connector problem area in the high-g environment is the use of conducting epoxy or eutectic bonds when constructing micro-circuits. In most cases connections of these types were found to be unreliable.

G. CRYSTALS

One of the major problem areas in high-g circuit design is that of frequency stability. Due to the inherent operating characteristics of standard quartz frequency control crystals they are required to have "voids" in order to allow mechanical vibration. This void along with the delicate mounting and connection methods have, until recently, precluded crystal use for high-g frequency stability due to physical failure of either the resonator or the mounting.

Relatively little work had been done in this area other than that reported by Harry Diamond Labs in reference 16 until a recent break-through by Bernstein at the Electronics Components Laboratory,

Army Electronics Command, Fort Monmouth, New Jersey. Bernstein reported the development of a "ruggedized" quartz crystal unit at the 1970 High-g Session of the International Telemetering Conference (reference 17). This "state-of-the-art" unit makes use of a thin layer of low stress nickel plated onto a chromium-copper film which is strongly adherent to the quartz for mechanical support of the resonator. Recent high-g tests of these units have resulted in 1 failure out of 18 at 15,000-g shock with as little as 4.6 ppm average stability at 16.5 and 19 MHz.

The "ruggedized" crystals are quite sensitive to mounting orientation. Figures 9 and 10 are sketches of the new type unit showing construction and performance of the crystals in 3 acceleration directions. Since these crystals are also sensitive to linear acceleration (reference 18) they may be utilized to measure "in barrel" acceleration in future generations of high-g tests.

H. DIODES

Encapsulated diodes ("Poly-Sil") and micro-diodes have high reliability rates while diodes in glass cases have a tendence toward structural failure.

I. ENCAPSULANTS (POTTING COMPOUNDS)

Many types of encapsulating materials were considered and utilized by the various testing agencies. The choice of an encapsulant should include consideration of several properties. The material should have a high yield strength and a low density to minimize mechanical loading on the components. It should have a low viscosity during pouring to insure flow around components without leaving voids

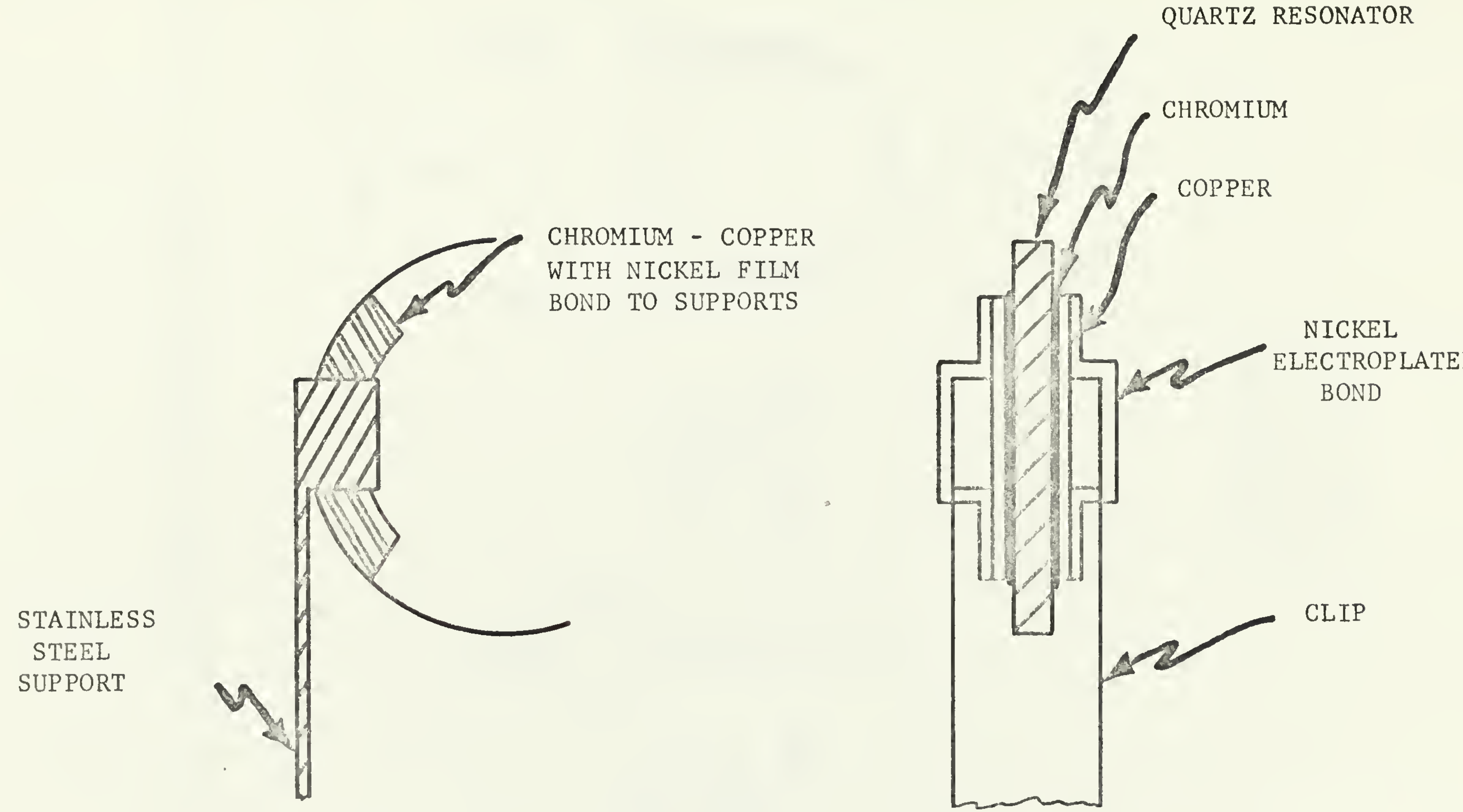

FIGURE 9 - CONSTRUCTION OF "RUGGEDIZED" CRYSTAL

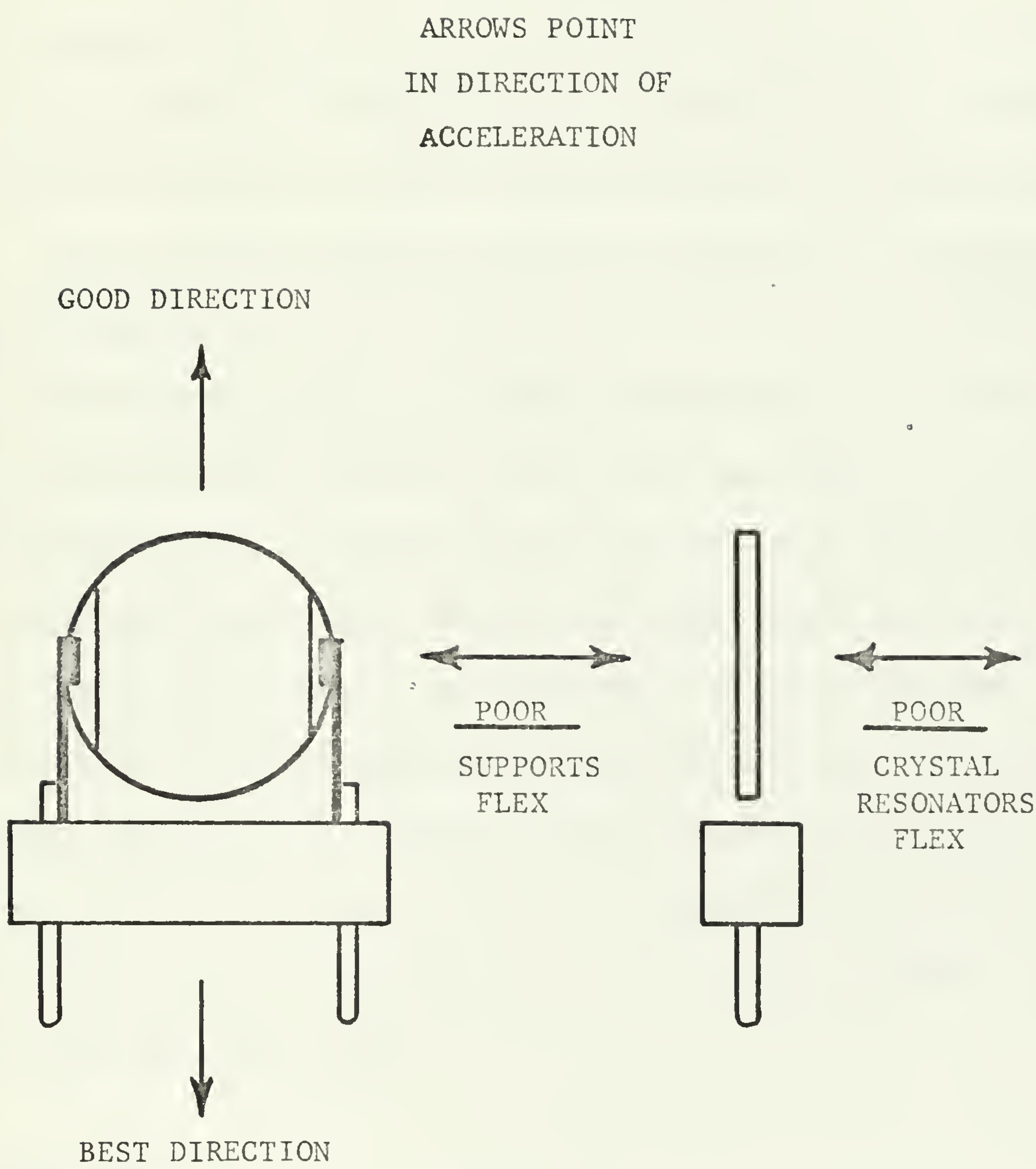

FIGURE 10 - RELATIVE PERFORMANCE OF "RUGGEDIZED" CRYSTAL IN THREE ACCELERATION DIRECTIONS

and should have a density approximately equal to the average density of the smallest components to be suspended in the compound. Also it should have a low curing temperature to insure against component damage or value change due to extreme exothermic curing.

For general VHF use (up to about 250 MHz) the most predominantly used potting material was Emerson and Cummings Stycast 1090 SI. This compound consists of glass microspheres and an epoxy resin binder. Tests reported by Space Research Corporation (reference 10) utilizing the Ballistic Research Laboratories test methods reported Stycast 1090 SI having survived launch accelerations of 88, 500-g.

For UHF use (up to about 2 GHz) and accelerations up to 50, 000-g the Ballistic Research Laboratories (reference 2) is using Emmerson and Cummings Stycast 35DS. This encapsulant is more viscous in its uncured state than 1090 SI but has acceptable qualities at UHF. It is a non-epoxy base cross linked polystyrene casting resin with silica microballoons as a filler. Table I shows the most recent UHF encapsulant desired and acceptable criteria in comparison with 35 DS.

Antenna casting or encapsulating is reported on in detail in the antenna section of this report.

J. INDUCTORS

Inductors are generally avoided in circuit design if possible because of their size. However, when this is not possible inductors may be wound on Pyrex coil forms which have been shown reliable by the Canadian Armament Research and Development Establishment (reference 19) and as reported by Space Research Corporation (reference 10). Small molded RF chokes such as those manufactured by Delevan, Jeffers and Nytronic have been shown to survive the environment.

High-g Encapsulant Parameter	Desired	Acceptable	E&C 35DS
Dielectric Constant at 1 GHz	$\leqq 1.2$	2 maximum	1.9
Dissipative Factor at 1 GHz	$\leqq 0.001$	0.005 maximum	< 0.001
Compressive Strength at $70^{\circ}F$	$>$ 5000 psi	2500 psi	5000 psi
Tensile Strength	Medium	Low	Medium
Flexural Modules	High	Medium	Medium
Temperature Range of Operation	-40° to $+400^{\circ}F$	0 to $+250^{\circ}$ F	-65° to $+300^{\circ}$ F
Mixed Viscosity	$\leqq$ 10,000 cP	$\leqq$ 45,000 cP	Very Thick
Cure Temperature	72° F	200° F	72° to 150° F
Cure Time	12 Hours	48 Hours	12 to 48 Hours
Specific Gravity	$\leqq 0.2$	0.8 maximum	0.7
Voids After Cure	$\leqq$ 1/64" dia.	1/32" dia. max.	1/32 - 1/16" dia.
Impact Strength	Very High	High	Not Available
Indent Hardness to 1/32" dia. Object	Very Hard	Hard	Very Hard
Thermal Conductivity	High	Medium	Medium
Exothermic Heating on Cure	Low	Low	Low
Shrinkage After Cure	$\leqq 0.1\%$	$\leqq 1\%$	Low
Expansion During Cure	Very Low	Low	Low
Long Term Chemical/Physical Stability	Stable	Stable	Stable
Moisture Absorption	Low	Low	Low
Chemical Reaction w/Plastic Components	Very Low	Low	Low

Table I - Encapsulant Specifications for UHF Circuits

In inductor applications where passive inductors are not available, or are not sufficient, the use of active inductors (i. e., negative impedance converters and gyrators) may be feasible utilizing proven components. Reference 20 contains an extensive review of these circuits.

K. INTEGRATED CIRCUITS/MICRO CIRCUITS

Integrated and microminiature circuits are undergoing rapid development for the high-g environment. These components have been investigated by a great number of activities and have been found basically capable of surviving the launch environment.

Integrated circuits such as the Westinghouse WC1709 have been extensively used by Space Research Corporation as operational amplifiers with entirely satisfactorily performance. Space Research Corporation has also used linear gates utilizing MOSFET's in the form of 16 channel multiplexers. These circuits use the Philco-Ford type pL4S16 integrated circuits. However, the reliability was unsatisfactory to the point that two or more circuits feeding in parallel path connection were required to afford sufficient redundancy for reliable operation.

Integrated circuits in TO-5 transistor cans.have low failure rates. Failures that have occurred have been attributed to mechanical damage to the bond of the wire connections to the chip, internal lead breakage and chip fracture. Some internal connection failures may be attributed to the type of bond used. Hybrid microminiature circuits for the circuit elements constructed on ceramic substrates were found to be more rugged than some monolithic circuits (reference 21).

L. PRINTED CIRCUITS

Printed Circuit techniques were, in general, avoided by most agencies for high component density packaging since small printed leads had a tendency to develop hairline cracks under high acceleration. Point to point wiring with small wire was found to be more reliable. A diversity of opinion in the type of wire best suitable for these applications is mentioned in this section under WIRE.

M. RESISTORS

Thin film resistors are preferred by Space Research Corporation (reference 10) since these tended to show the least change in value due to gun launching. Value changes as reported by Aviation Electric, Limited (reference 14) and the Geophysics Corporation of America (reference 22) indicated an increase in resistance of less than 3% for most thin film resistors while carbon composition resistors tended to have changes ranging between -2% to +18%.

Ballistic Research Laboratories (reference 21) have found that biterminal cylindrical components with axial leads such as molded carbon resistors may be made more reliable if they are laid flat on the mounting deck without tension on their leads. Therefore, it is considered that fixed resistors of either type are reliable for the high-g environment. The selecting of one over the other depends primarily on circuit sensitivity to value changes.

Potentiometers and "Trimpots" have also been extensively tested and are in general to be considered reliable. However, significant changes in value are to be expected depending upon the orientation in the circuit (reference 21).

N. SOLISTRON

This component perhaps more properly could have been categorized as a transistor or a semiconductor. It has, however, been chosen to report it separately due to its "state-of-the-art" development and unique properties. The solistron is a solid state klystron operating in the 1700 to 2000 MHz range with an output power of approximately 150 milliwatts. This component, developed by Western Microwave, has been further modified to serve as a high-g launch hardened component. It is a temperature sensitive device; therefore, due to the high aerodynamic heating of a high velocity projectile, it requires special mounting techniques in order to be considered reliable. The latest reported component had been sufficiently ruggedized and miniaturized to allow the use of sufficient additional insulation to insure reliable operation. The present component is cylindrical 1.125 inches in diameter and is 1 inch long. In actual test conducted by the Ballistic Research Laboratories (reference 21) in an environment of approximately 45,000-g one of twelve failed. This device was actually designed into and used for Ballistic Research Laboratories projectile telemetry and had two failures out of twelve launches in 5 inch and 16 inch guns. Due to the need for a device of this type and its small size and high frequency operating capabilities, it is considered to be reliable within the "state-of-the-art".

O. TRANSISTORS

Solidly potted transistors and small encapsulated chip transistors have been shown to have high reliability rates. Many types of conventional transistors (planar construction) have withstood launch

accelerations as have several epitaxial transistors. It has been found by the Ballistic Research Laboratories (reference 21) that conventional planar transistors in TO-5 and T-18 packages were more reliable if they were oriented in such a direction that the acceleration vector was parallel to a radius of the transistor can.

P. WIRE AND CIRCUIT CONNECTIONS

As previously stated printed circuit connection techniques are avoided due to their tendency to develop hairline cracks; therefore, point to point wiring has been shown to be the most reliable technique.

Space Research Corporation (reference 10) has found that stranded hookup wire with polyvinylcloride (PVC) insulation is preferred over teflon due to the improved bonding of the encapsulating material. On the other hand Ballistic Research Laboratories (reference 21) recommends the use of small teflon coated wire and gives no indication of failure of the encapsulating material to adhere to the insulation.

It is considered that either type insulation is sufficient up to about 30, 000-g. For accelerations in excess of 30, 000-g the PVC insulation should provide a more solid unit and will therefore prove more reliable.

Q. MISCELLANEOUS

There are obviously many types of electronic circuit components that have not been specifically addressed in the preceding paragraphs. It may be summarized to observe that the majority of standard "off-the-shelf" electronic components have been proven reliable in the gun launch environment. However, some parameter value changes must be expected and anticipated in the circuit design. Designs should be

sufficiently flexible to allow for these parameter changes or sufficient predesign testing of the component in question should be accomplished before its use as a circuit component.

Many devices such as thermisters, hardened IR sensors, voltage sensitive switches, photovoltaic cells, fiber optics, solar sensors, accelerometers, etc., have been reliability utilized by agencies involved in the development and use of gun launched electronic devices.

R. SUMMARY

The unavoidable change in parameter values of most all components subjected to the high-g environment may be used to advantage in self compensating circuit design if the following criteria could be met.

1. Components must be designed and constructed such that the parameter changes are repeatable with a higher degree of reliability than is now available.

2. Methods of parameter evaluation in a more precise manner must be instituted.

IV. CONSTRUCTION AND ASSEMBLY TECHNIQUES

A. GENERAL

It has been determined by several agencies that conventional circuit board construction techniques using small wire to connect components are adequate for the high-g environment provided the complete assembly is encapsulated in a compound to render it immovable. Printed circuit leads are avoided due to development of hairline cracks. The components used must be able to withstand the high accelerations.

Some components are capable of withstanding these accelerations in their "off-the-shelf" configuration while others must be specially designed or modified for high-g use. This modification consists primarily of "hardening" the component. For instance, the case of a semiconductor may be opened and the semiconductor case filled with a compound compatible with that used to encapsulate the entire assembly. This procedure eliminates the transistor case void within the completed assembly.

The Ballistic Research Laboratories (reference 2) has recently completed a study of currently available low loss encapsulants with sufficient strength to withstand in excess of 50,000-g accelerations. In general these encapsulants have a dielectric constant of about 2. Although this is not a large value for a dielectric it has been determined that surrounding a UHF (approximately 1.8 GHz) oscillator or amplifier circuit with such a dielectric can change the frequency several hundred MHz from the initial unencapsulated frequency. Of

equal importance this procedure often significantly reduces the efficiency and stability as a result of changes in capacitive feedback and mutual coupling between circuit elements.

At the present time only one encapsulant, Emmerson and Cummings Stycast 35DS, has been found acceptable for UHF use. This potting material is a crosslinked polystyrene casting resin with silica micro-balloons as a filler. The encapsulants previously used for VHF and lower frequency circuits (EPON 815 and Stycast 1090SI) are too lossy; their dielectric constants are too large for use at UHF. The strength and UHF loss properties of 35DS are acceptable with very good results having been obtained using this material for supporting circuit components for use in the 1500 to 1800 MHz range. However, even with the rather low dielectric constant of 2 the circuits must be carefully adjusted in the presence of the dielectric.

The Ballistic Research Laboratories have also developed a tuning technique where the transmitter chassis is filled with a dielectric powder which simulates the electrical properties of 35DS and the circuit is adjusted for optimum performance. The powder is then removed and the encapsulant applied.

Some difficulty has been experienced with voids in the 35DS which can be reduced by filling the chassis very slowly and vibrating it after it is filled.

Caution must be exercised when selecting an encapsulant for use in the high-g environment as some encapsulants produce heat during their cure which is sufficient to itself damage the components. In addition the encapsulating material must have a thermal conductivity sufficient to allow at least a moderately efficient use of the individual

component's power handling capability. Failure to select a compound with high thermal conductivity has been shown to reduce the efficiency of circuit design by about 80% (reference 14). In this case a transmitter designed to produce a 5 watt output was capable of outputs less than 1 watt without self generated heat damaging the circuitry.

B. CIRCUIT DESIGN AND COMPONENT SELECTION

The circuit design must be compatible with the space available in the vehicle of intended use considering circuit function and proven components available. Also, depending on the expected environment, sufficient room must be allowed for insulation to reduce the effects of launch and aerodynamic heating and upper atmosphere cooling. The circuit layout should consider orientation of those components sensitive to oriented mounting.

Should it be necessary to use "un-proven" components the components selected can be hardened if necessary and pre-tested using the methods specified in references 2, 21 and 22. These methods are outlined in the following paragraphs.

1. Components should be selected using the criteria outlined in Section III of this report. They should have small mass and have a rugged monolithic construction or be capable of "hardening" into solid structures. The components selected should be of the most dependable quality available to avoid failures due to non-high-g causes.

2. If the components selected contain voids in their "off-the-shelf" configurations they must be "hardened" by filling all voids with an epoxy resin. Detailed procedures for accomplishing this are difficult to prescribe due to the variety of construction methods used by industry.

The general method is to open the container or case in an atmosphere compatible to the contents. (i.e., Transistor junctions exposed to air will rapidly degrade if not isolated from the gases in the atmosphere, etc.) The void is then filled using an encapsulant compatible with both the component and the encapsulant to be used to encase the entire circuit. Extreme caution must be exercised at this point to provide a good mechanical bond and still preclude the effects of exothermic curing.

When the above procedure is completed a thorough functional electrical check of the component should be made to determine and evaluate any parameter changes. These changes, if any, will then allow reevaluation of use in the intended circuit.

3. Selected and/or hardened components should be high-g tested in minimum lots of about 12. They are mounted on fiberglass boards and supported by the soapstone method (reference 2) for intended environments up to 50,000-g. For higher environments the components must be hard mounted using the normal circuit encapsulation techniques outlined below. Following test the encapsulant must then be dissolved away and the components tested. Some non-high-g damage may be incurred using the latter procedure.

The test assemblies should then be subjected to the maximum acceleration expected a minimum of three times. The criteria used for acceptance by the Geophysics Corporation of America is no more than one failure out of twelve components subjected to three successive tests.

4. A test or "bread-board" circuit may now be constructed to allow overall circuit evaluation.

C. CIRCUIT ASSEMBLY AND PACKAGING

Conventional circuit board assembly techniques are used with small insulated wire connections. Both flat board and cordwood type construction have been successfully used in acceleration environments up to 550, 000-g (reference 23).

If circuit tuning is required it may best be accomplished by packing the assembly in a powder or liquid with dielectric properties as similar as possible to the intended encapsulant. If a powder is used it may be compressed around the assembly by the "soapstone" method previously explained. This tuning technique allows rapid access to the circuit elements while closely approximating the encapsulated state.

The completely wired, tested and tuned circuit is then supported in a teflon coated mold and encapsulated with a material with adequate properties for the use intended. Selection of an encapsulant should include consideration of thermal conductivity and exothermic heating while curing as well as electrical and methanical strength properties. Emmerson and Cummings Stycast 1090SI and 35DS encapsulants have been used with a high degree of success by several agencies.

Most conventional mold configurations (for projectile use) are cylindrical with one side flat to allow terminal connections. Some circuit assemblies have also been cast with a hole thru the center for wiring (hollow cylinder) when they are to be used as subassemblies to be interconnected with those on either side. Most encapsulants used for high-g assemblies may be "tooled" to exact size after molding if necessary or desired.

In some cases it may be necessary to calibrate the circuit (determine outputs for prescribed inputs) prior to final assembly into the

flight configuration. This may be done by conventional means after the circuit construction and encapsulation is completed.

When ultimately mounted the remaining voids (for terminal connections or wiring) may, depending on the expected environment, also be filled with an encapsulating material.

D. TESTING

In order to insure desired performance the entire circuit assembly must be tested in its final packaged form. This may be accomplished by any of the methods provided in Section II of this report.

V. CONCLUSIONS AND RECOMMENDATIONS

It is concluded from this study that present test methods and procedures are insufficient to support or deny reversible high-g effects on components. Present methods are, however, sufficient to show that components and circuit construction/assembly techniques are satisfactory up to about 50, 000-g with some tests conducted indicating probable adequacy to acceleration magnitudes on the order of 550, 000-g.

These methods are only adequate to show gross survivability; there is little evidence of quantitative evaluation. For the most part present tests are of the "go, no-go" variety; either a component survives or not. These tests do provide a reasonable degree of repeatability with respect to gross survivability. It therefore suffices to say that present test methods are acceptable but not sufficiently detailed for precision design uses such as guided projectiles, homing projectiles, precision fuzing, etc.

It is recommended that further studies be initiated utilizing "state-of-the-art" developments to provide precise in-barrel data with respect to the acceleration profile. This may be accomplished by centrifuge calibration of crystal frequency shift (ppm/g) and use of the Sandia method to telemeter this in-barrel data to a monitoring point. Once the acceleration profile is precisely known, or measurable with a high degree of accuracy, other component operation can be dynamically monitored during and after the in-barrel acceleration.

It is further recommended that the above program be followed by thorough analysis of the failure or parameter change mechanisms with

the end goal of eliminating these deficiencies. This will allow production of a complete line of high-g hardened and calibrated components. Circuits may then be designed using reliable and repeatable design parameters to provide the desired circuit performance by generally conventional methods. Replacement of the present "trial-and-error" circuit design technique will allow a wide scope of precision weaponry heretofore unavailable.

APPENDIX A

The following table contains a consolidation of data from several agencies that have tested and/or reported on components capable of withstanding the high-g launch environment. In some cases the reference material available reported on tests conducted by other activities; therefore, these data have been screened to remove duplication. The table is arranged alphabetically by component nomenclature and sub-arranged by manufacturer and part number. (Semiconductors are arranged by part number.) Each listing gives one or more references in abbreviated form to facilitate ease in acquiring more detailed information where desired.

Since many components have been tested by more than one agency under different test conditions no attempt has been made to catagorize components by their "g" capability. It may be assumed that all components listed are capable of survival of at least 10,000-g smooth bore launches. Particular cases where components have been shown to significantly exceed this limit or where they have been tested by a single source the "g" limit is specified in the remarks section. An attempt has been made to cite only references to the originating activity.

Failure to include components in this list should not be construed as precluding their suitability for high-g use nor should it serve as an indication that they have not been tested for this use. However, the inclusion of components is intended to accurately represent their suitability within the limits specified and under the conditions given in the references.

A key to the reference code, although standard, is given on the last page of the table.

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Battery	Eveready	B225T	SRC-R-28	Nickel Cadmium, tested 15,000-g smooth bore and 10,000-g/200 rps rifled, reported 99% reliable by SRC
Battery	Eveready	E-400	GCA-TR-65-15-G	
Battery	Gould	100mch	GCA-TR-65-15-G	Mercury
Battery	Gould	225BH	BRL-1749	Nickel Cadmium, survived 50,000-g
Battery	Gould	VB25	BRL-1749	Nickel Cadmium, survived 50,000-g
Battery	Gulton	VO-250	BRL-1632 BRL-1651	Has 10 minute life after shock, requires potting
Battery	Mallory	RM-42R	BRL-1749	Mercury, survived 50,000-g
Battery	Mallory	RM-400	BRL-1749	Mercury, 4 of 14 failed 3rd successive test, all survived tests 1 and 2
Battery	Mallory	RM-625	CARDE 522/65	Mercury
Battery	Mallory	TR-132R	BRL-1749	Mercury, survived 50,000-g
Battery	Sandia	G2606-A2	ITC-70	Liquid Ammonia, tested to 12,500-g with 5200 rps spin rate, must be center-line mounted to prevent shorting of plates, "in-house" development
Battery	Yardney	PM05	BRL-1749	Silver Cell, survived 50,000-g

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Bolometer	Barnes	2-103	AETR 13565	Also tested satisfactory by BRL
Capacitor	ALCO	DM5	SRC-R-28	Dipped silver mica recommended for use by SRC where small values are required
Capacitor	Centralab	Trimacon	SRC-R-28	Centrifuge tested by Aerospace Corp. for SRC
Capacitor	Components, Inc.	G106	GCA-TR-65-15-G	"Minitan" miniature tantalum polarized
Capacitor	Components, Inc.	G106R	BRL-1749	"Minitan" miniature tantalum polarized
Capacitor	Components, Inc.	L10	GCA-TR-65-15-G	"Minitan" miniature tantalum polarized
Capacitor	Components, Inc.	S22	GCA-TR-65-15-G	"Minitan"
Capacitor	Components, Inc.	Y102A	GCA-TR-65-15-G	"Minitan"
Capacitors	Components, Inc.	1000 pF to 1.0 μF	BRL-1749	"Minitan" miniature tantalum unpolarized, survived 45,000-g when mounted radially and 50,000-g when mounted axially
Capacitor	Corning	CY	AEDC-TN-60-214	
Capacitor	Corning	CY20	GCA-TR-65-15-G	

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Capacitor	Corning	CY20C	BRL-1749	
Capacitor	Dervax		GCA-TR-65-15-G	Miniature electrolytic
Capacitor	Erie	Red Cap	SRC-R-28	Mica, suitable for small value use only
Capacitor	Erie	362	SRC-R-28	Feed thru
Capacitor	Erie	2404	SRC-R-28	Feed thru, ceramic
Capacitor	Erie	2425	SRC-R-28	Feed thru, ceramic
Capacitor	Erie	3115	SRC-R-28	Trimmer, also centrifuge tested by Aerospace Corporation
Capacitor	JFD	MT-150	BRL-1749	Miniature trimmer, survived 3 successive tests to a maximum of 43,000-g, largest change 30%
Capacitor	Johanson	3-30 pF	BRL-1749	Miniature trimmer, 100% survival at 40,000-g after modification by BRL, unmodified units had value changes and 2 of 11 tested failed completely (open circuited)
Capacitor	Kemet	KIC75K	SRC-R-28	Epoxy molded, polarized, also centrifuge tested by Aerospace Corporation
Capacitor	Mallory	1147	AETR 13565	Solid tantalum, PVC

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Capacitor	Mallory	Tap	AETR 13565	Tantalum wet slug
Capacitor	Phillips	A1	AETR 13565	Paper
Capacitor	Semcor	TS05	AETR 13565	Solid tantalum
Capacitor	Sprague	1550	BRL-1749	3 of 10 tested failed
Capacitor	Sprague	164D	AETR 13565	Solid Tantalum, 1 of 6 tested failed
Capacitor	Sprague	190D	AETR 13565	Solid Tantalum
Capacitor	Texas Inst.	ECM2	AETR 13565	Solid Tantalum
Capacitor	Vitramon	VK30CW	GCA-TR-65-15-G	
Capacitor	Vitramon	VY	GCA-TR-65-15-G	
Capacitor	Voltronics	3-30 pF	BRL-1749	Miniature trimmer, 3 successive tests to a maximum of 43,000-g, largest change 17%
Capacitor	Wescon	32M	AETR 13565	Mylar
Capacitor	Wescon	32P	AETR 13565	Mylar
Coil Form	Pyrex		CARDE 522/65	
Diode		1N82AG	SRC-R-28	Point contact diode, centrifuge tested at 18,000-g for 40 sec. by Bendix

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Diode	North American Electronics	1N709	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N710	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N711	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N717	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N718	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N718	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North American Electronics	1N719	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially
Diode	North Amer. Elec.	1N720	BRL-1749	Zener, "Poly-Sil" construction, survived 40,000-g when mounted radially

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Diode	Sylvania	1N831	SRC-R-28	Centrifuge tested to 24,000-g for 30 sec. by Bendix, flight tested by SRC
Diode	Sylvania	1N832	SRC-R-28	Point contact
Diode	TRW	1N897	AETR 13565	
Diode	Transitron	1N1779	BRL-1749	Zener, survived 45,000-g mounted axially
Diode		1N4003	SRC-R-28	Flight tested by NWL/D at 12,000-g/ 200 rps spin in 155mm projectile
Diode	Fairchild	FSP-55	SRC-R-28	Centrifuge tested to 25,000-g for 30 sec. by Bendix
Diode	Philco	L 4156	SRC-R-28	Alloyed junction, pill package
Diode	TRW	PD101	BRL-1651	Survived 60,000-g
Diode	TRW	PD102	BRL-1749	Survived 50,000-g
Diode	TRW	PD103	BRL-1749	Survived 50,000-g
Diode	TRW	PD106	AETR 13565	
Diode	Unitrode	UT-23	AETR 13565	
Encapsulant	Hybrid		BRL-1566	EPON-815, Thiokol LP-3 60/40 with DELTA catalyst 100/6 parts, originally used by BRL at VHF

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Encapsulant	Hybrid		CARDE 522/65	Hybrid mix: Araldite 502 with CIBA Co. HN 951 hardener
Encapsulant	Hybrid		SRC-R-28	Hybrid mix: Sand/Hysol combination, survived 41,300-g impact with 100% failure at 67,000-g
Encapsulant	Hybrid		SRC-R-28	Hybrid mix: Echosphere/Hysol combination failed impact test at 46,500-g
Encapsulant	3-M	Scotchcase 8	ITC-70	Used by Sandia for hardening micro-miniature circuits to survive 12,500-g at 5200 rps spin rate
Encapsulant	Emerson and Cummings	Stycast-1090SI	SRC-R-28 CARDE 522/65 BRL-1651	Survived impact test of 88,500-g using BRL "round nose cone", 2 of 3 units tested with 75° nose cone failed at 72,300-g, has good VHF properties
Encapsulant	Emerson and Cummings	Stycast 35-36 series	BRL-1486	Non-epoxy base potting compound, too viscous for intricate circuits but has better properties than 1090SI for VHF use
Inductor	Delevan	MS18130	SRC-R-28	
Inductor	Jeffers		SRC-R-28	
Inductor	Nytronic		SRC-R-28	Molded dc inductor series

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Integrated-Circuit	Westinghouse	WC 1709	SRC-R-28	Operational amplifier, satisfactory for high-g use only if well supported in the area of bonded wire connections
Integrated-Circuit		709C	SRC-R-28	Flight tested by NWL/D to 12,000-g with 200 rps spin rate, solidly potted into total assembly
Matching-Network	Vanguard Electronics		SRC-R-28	Special construction, potted into 0.3 x 0.3 x 0.3 inch maximum assembly
Micro-Circuit	Fairchild	μL 702	GCA-TR-65-15-G BRL-1749	Amplifier circuit, TO-5 case
Micro-Circuit	Fairchild	μL 903	GCA-TR-65-15-G BRL-1749	Gate circuit, 100% survival when TO-5 case potted, 3 of 6 tested failed without potting
Micro-Circuit	Philco	PA 7600	SRC-R-28	10 lead TO-5 case, potted, test flown as transmitter IF amplifier
Potentiometer	Bourns	3250P-1-103	AETR 13565	"Trimpot"
Potentiometer	Conello		BRL-1749	2 K, survived 53,000-g with largest value change 3.6%
Potentiometer	Minelco		BRL-1749	5 and 10 K, survived 43,000-g with largest value change 3.5%

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Resistor	Allen-Bradley	TR	AETR 13565 GCA-TR-65-15-G	Carbon composition 1/10 and 1/8 watt
Resistor	Allen-Bradley	BB, CB, EB	SRC-R-28 GCA-TR-65-15-G	Fixed composition 1/8, 1/4, 1/2 watt
Resistor	Allen-Bradley	PB	SRC-R-28	Molded carbon 1/4 watt
Resistor	ACI	RN60C	GCA-TR-65-15-G	
Resistor	ACI	SCS	CARDE 522/65	Metal film
Resistor	Electra	RN60D	GCA-TR-65-15-G	
Resistor	IRC		GCA-TR-65-15-G	Carbon composition 1/2 watt
Resistor	IRC	MEA, MMF	CARDE 522/65	Metal film
Resistor	Metohm	RN60C	BRL-1749	1 of 6 tested open after test
Resistor	Ohmite	Little-Devil	AETR 13565	Carbon composition 1/10 and 1/4 watt survived various tests to 65,000-g
Resistor	Sprague		AETR 13565	Metal film
Resistor	RPC		BRL-1749	Carbon film, 1 of 12 tested failed on 3rd successive test
Resistor	Welwyn	F-25, F-20 N-12 and 401	AETR 13565	Tin Oxide

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Solistron	Western-Microwave	SFL-4020	BRL-1749	Solid state klystron tested to 45,000-g, very temperature sensitive
Thermistor	Fenwall	GB 31J4	GCA-TR-65-15-G	Successfully launched by SRC at 45,000-g
Thermistor	Gulton		BRL-1749	Survived 45,000-g
Thermistor	Phillips	B832002/1k	SRC-R-28	
Thermistor	Veco		BRL-1749	Survived 45,000-g
Transistor		2N128	AEDC-TN-60-214	Potted before test
Transistor	RCA	2N173	BRL-1749	Must be potted to survive 50,000-g, unpotted units failed due to chip fracture
Transistor	RCA	2N301	BRL-1749	Unpotted units failed due to chip fracture potted units survived 50,000-g
Transistor		2N345	AEDC-TN-60-214	Potted before test
Transistor		2N384	AEDC-TN-60-214	Potted before test
Transistor		2N502	BRL-1566	
Transistor		2N537	BRL-1566	
Transistor		2N667	BRL-1566	
Transistor		2N697	BRL-1566	

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Transistor		2N700	CARDE 255/59	Potted before use
Transistor	Fairchild	2N706	CARDE 522/65	Satisfactory performance without potting
Transistor	Texas Inst.	2N849	BRL-1749	Survived 50,000-g
Transistor		2N1505	BRL-1566	Successfully launched as system component
Transistor		2N1671	BRL-1566	Successfully launched as system component
Transistor		2N1711	BRL-1749	2 of 12 tested failed
Transistor	General Elec.	2N2040	GCA-TR-65-15-G	Potted
Transistor	Sperry	2N2590	BRL-1749	Survived 30,000-g axially
Transistor	Sperry	2N2602	SRC-R-28	Potted by GCA before test
Transistor	General Elec.	2N2647	BRL-1749	Survived 30,000-g axially
Transistor	General Elec.	2N2711	BRL-1749	Survived 60,000-g
Transistor	General Elec.	2N2712	BRL-1566	
Transistor	General Elec.	2N2713	BRL-1749	Survived 45,000-g
Transistor	General Elec.	2N2714	BRL-1651	Survived 60,000-g
Transistor	General Elec.	2N2926	AETR 13565	

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Transistor	Fairchild	2N3277	GCA-TR-65-15-G	F.E.T. potted before use
Transistor	Motorola	2N3375	SRC-R-28 HDL 65-33 BRL-2055	Successfully launched as system component Satisfactory performance without potting Survived 100,000-g in BRL tests
Transistor	Motorola	2N3480	BRL-1749	Uni-junction chip, 100% survival
Transistor	Texas Inst.	2N3480	GCA-TR-65-15-G	5 of 9 tested failed when case potted by SRC
Transistor	National Semiconductor	2N3546	GCA-TR-65-15-G	
Transistor	National Semiconductor	2N3547	BRL-1749	Microtransistor
Transistor		2N3553	BRL-2055	Survived 100,000-g
Transistor	Fairchild	2N3638	BRL-1749	Survived 45,000-g
Transistor	Fairchild	2N3639	BRL-1749	Survived 45,000-g
Transistor	Texas Inst.	2N3702	SRC-R-28	Potted by Manufacturer
Transistor	Texas Inst.	2N3704	SRC-R-28	Successfully launched as system component
Transistor	Motorola	2N3733	SRC-R-28	

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Transistor		2N3819	SRC-R-28	
Transistor		2N3820	SRC-R-28	
Transistor	TRW	2N4040	SRC-R-28	Centrifuge tested to 22,500-g by Bendix
Transistor	ITT	3TE440	SRC-R-28	Centrifuge tested to 21,500-g by Bendix
Transistor	Crystalonics	C622	BRL-1749	3 of 4 tested survived 50,000-g when mounted radially, none survived when mounted axially
Transistor	Fairchild	FI100	BRL-1749	Survived 33,000-g
Transistor	Fairchild	FK918	SRC-R-28	Centrifuge tested to 25,000-g by Bendix, potted
Transistor	Fairchild	FSP42	BRL-1749	Survived 58,000-g
Transistor	Fairchild	FSP165	BRL-1749	Survived 58,000-g
Transistor	Fairchild	FSP242	BRL-1749	Survived 58,000-g
Transistor	Motorola	MU970	GCA-TR-65-15-G	Potted
Transistor	National Semiconductor	NS7070	GCA-TR-65-15-G	
Transistor	National Semiconductor	NS700	BRL-1749	

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Transistor	Sperry	P21C312	GCA-TR-65-15-G	Potted
Transistor	Philco	pL4S16	SRC-R-28	MOSFET, for reliable operation must use 2 or more in parallel due to lead breakage
Transistor	Vector	S-3006	SRC-R-28	Successfully launched as system component, test launched by NWL/D at 12,000-g with 200 rps spin rate
Transistor	Texas Inst.	SJ993	BRL-1749	Unijunction
Transistor	Texas Inst.	TI 415	AETR 13565	1 of 10 tested failed
Transistor	Texas Inst.	TIC 45,46,47 series	SRC-R-28	Successfully used by SRC
Transistor	Texas Inst.	TIS 43	SRC-R-28	Used by SRC in HF applications
Transistor	Texas Inst.	TIS 80 series	SRC-R-28	Successfully used by SRC
Transistor	Texas Inst.	TIS 83	SRC-R-28	Successfully launched as system component, test launched by NWL/D at 12,000-g with 200 rps spin rate
Transistor	Texas Inst.	TIX3016A	SRC-R-28	Centrifuge tested to 25,000-g by Bendix, top removed and potted
Varactor	Motorola	1N4383	SRC-R-28	Potted, used as transmitter doubler

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

COMPONENT	MANUFACTURER	NUMBER/TYPE	REFERENCE(S)	REMARKS
Varactor	Motorola	1N5151	SRC-R-28	
Voltage Sensitive Switch	Sprague		BRL-1749	Survived 3 successive tests to 49,000-g

KEY TO REFERENCE CODES

AEDC	Arnold Engineering Development Center, Tullahoma, Tennessee
AETR	Aviation Electric, Limited, Montreal, P.Q., Canada
BRL	Ballistic Research Laboratories, Aberdeen, Maryland
CARDE	Canadian Armament Research and Development Establishment, Valcartier, P.Q., Canada
GCA	Geophysics Corporation of America, Bedford, Massachusetts
HDL	Harry Diamond Labs, Washington, D. C.
ITC-70	International Telemetering Conference Proceedings (IEEE sponsored, Oct. 70) Los Angeles, California
NWL/D	Naval Weapons Laboratory, Dahlgren, Virginia
R	Report
SRC	Space Research Corporation, Newport, Vermont
TM	Technical Memorandum
TN	Technical Note
TR	Technical Report

COMPONENTS SUITABLE FOR USE IN HIGH-G ELECTRONICS CIRCUITS

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13. ABSTRACT

High-g acceleration produced by large bore guns is compared with impact acceleration. Methods for subjecting electronic components and circuit packages to high-g launch environments up to 550,000-g are outlined and analyzed. An analysis of the effect of the high-g environment on components is performed on a component by component basis. Methods for selecting, "hardening" and testing components for high-g circuitry are given as are circuit construction and assembly details. An extensive appendix listing type, manufacturer and part number is included for components that have survived high-g environmental testing. Recommendations are made for an improved test program that will yield a new generation of reliable high-g hardened components for circuit design.

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Electronic Component Test						
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